

MOLECULAR CLOUD EVOLUTION III. ACCRETION VS. STELLAR FEEDBACK

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ABSTRACT

We numerically investigate the effect of feedback from the ionizing radiation heating from massive stars on the evolution of giant molecular clouds (GMCs) and their star formation efficiency (SFE), which we treat as a time-dependent quantity. We consider the GMCs' evolution from their formation by colliding warm neutral medium (WNM) streams up to advanced star-forming stages. We find, in agreement with our previous studies, that the star-forming regions ("clouds") within the GMCs are invariably formed by gravitational contraction, so that their internal non-thermal motions must contain a significant component of global convergence, which does not oppose gravity. After an initial period of contraction, the collapsing clouds begin forming stars, whose feedback evaporates part of the clouds' mass, opposing the continuing accretion from the infalling gas. The competition of accretion against dense gas consumption by star formation (SF) and evaporation by the feedback, regulates the clouds' mass and energy balance, as well as their SFE. We find that, in the presence of feedback, the clouds attain levels of the SFE that are consistent *at all times* with observational determinations for regions of comparable SF rates (SFRs). However, we observe that the dense gas mass is *larger* in general in the presence of feedback, and that the total (dense gas + stars) is nearly insensitive to the presence of feedback, suggesting that the total mass is determined by the accretion, while the feedback inhibits mainly the conversion of dense gas to stars, because it acts directly to reheat and disperse the gas that is directly on its way to forming stars.

We find that the factor by which the SFE is reduced upon the inclusion of feedback is a decreasing function of the cloud's mass, for clouds of size ~ 10 pc. This naturally explains the larger observed SFEs of massive-star forming regions. We also find that the clouds may attain a pseudo-virialized state, with a value of the virial mass very similar to the actual cloud mass. However, this state differs from true virialization in that the clouds are the center of a large-scale collapse, continuously accreting mass, rather than being equilibrium entities. Finally, we also calculate the density probability density functions of the clouds, finding that they in general exhibit the bimodal shape characteristic of thermally bistable flows, rather than a lognormal form, which is characteristic of isothermal flows. This supports suggestions that low density, atomic gas pervades molecular clouds. We conclude that the general state of star-forming regions is likely to be one of gravitational collapse, although most of the mass in a GMC may be not participating of the instantaneous star-forming activity, as recently suggested by Elmegreen (2007); that is, that SF is a spatially and temporally intermittent phenomenon, with strong, localized bursts interspersed within much more quiescent gas.

Subject headings: interstellar matter – stars: formation – turbulence

1. INTRODUCTION

The evolution of giant molecular clouds (GMCs) is a key ingredient in our understanding of the star formation process. In particular, the low observed star formation efficiency (SFE) at the scale of whole GMCs ($\sim 2\%$; Myers et al. 1986) remains a topic of strong debate, with there being two main competing scenarios that attempt to explain it. These scenarios refer essentially to the effect of the stellar feedback (mainly from massive stars) on the star-forming clouds. One is the scenario that the stars quickly disrupt their parent clouds by dispersal and/or photoionization, before the gaseous mass of the cloud is completely converted to stars (e.g. Whitworth 1979; Elmegreen 1983; Franco, Shore & Tenorio-Tagle 1994; Williams & McKee 1997; Hartmann, Ballesteros-Paredes & Bergin 2001). In

this case, the SFR of active star-forming sites may be large for brief periods, and then halted by the very stars that have just been formed.

In the other scenario, the role of stellar feedback is to drive turbulent motions within the GMC, which oppose its self-gravity, allowing it to remain in near hydrostatic equilibrium for times significantly longer than its free-fall time (t_{ff}) (Krumholz & McKee 2005; Krumholz, Matzner, & McKee 2006; Li & Nakamura 2006). In this case, the low efficiency of star formation would be due to the dual role of supersonic turbulence in self-gravitating clouds, of opposing global collapse of the cloud while promoting local collapse of turbulent density enhancements, which involve small fractions of the total cloud mass (Klessen, Heitsch & Mac Low 2000; Vázquez-Semadeni, Ballesteros-Paredes, & Klessen 2003, see also the reviews by Mac Low & Klessen 2004; Ballesteros-Paredes et al. 2007).

Another controversy, related to the control of the SFE, refers to the nature of the motions originating the

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linewidths observed in GMCs and their substructure. The latter were initially proposed to correspond to gravitational contraction by Goldreich & Kwan (1974), but this suggestion was quickly deemed untenable by Zuckerman & Palmer (1974), who noted that it would imply total Galactic SFRs of the order of the total molecular gas mass in the Galaxy ($\sim 10^9 M_\odot$) divided by the typical free-fall time for a GMC (~ 4 Myr), or $\sim 250 M_\odot \text{ yr}^{-1}$, an estimate roughly two orders of magnitude larger than the observed Galactic SFR. Zuckerman & Evans (1974) then suggested that the observed linewidths could correspond instead to random, small-scale² turbulent motions, a notion that has prevailed until the present. However, a number of workers have recently advocated a return to the gravitational contraction picture, noting that various observational properties of clouds and clumps can be well matched by models dominated by gravitational contraction (e.g., Hartmann & Burkert 2007; Peretto, Hennebelle & André 2007; Vázquez-Semadeni et al. 2009). Moreover, the notion of completely random, small-scale turbulent motions appears difficult to reconcile with the recent realization that the principal component of the velocity differences within clouds and clumps at all scales appears to be “dipolar”, indicative of coherent motions at the scale of the whole cloud or clump (Heyer & Brunt 2007; Brunt et al. 2009). In general, several studies comparing simulations and observations have concluded that the motions in molecular clouds are consistent with large-, rather than small-scale driving (Ossenkopf & Mac Low 2002; Brunt 2003; Padoan et al. 2009).

If a return to the collapsing scenario is to be considered, it is necessary to somehow avoid the Zuckerman & Palmer (1974) criticism of it. This is actually not so difficult because that criticism neglects the internal structure of the GMCs. Recent numerical studies of cloud formation by converging streams of warm neutral gas in the interstellar medium show that the clouds are born turbulent, due to one or more of the thermal, thin-shell, and Kelvin-Helmholtz instabilities (Hennebelle & Péroult 1999; Koyama & Inutsuka 2000; Koyama & Inutsuka 2002; Audit & Hennebelle 2005; Heitsch et al. 2005; Vázquez-Semadeni et al. 2006). The turbulence is subsonic with respect to the warm gas, but supersonic with respect to the cold phase, implying large density fluctuations in the latter. In fact, it has recently been proposed that molecular clouds may actually contain a warmer, atomic substrate in which colder molecular clumps are embedded (Hennebelle & Inutsuka 2006). In either case, the molecular cloud contains large, *nonlinear* density enhancements in which the local free-fall time is significantly shorter than the cloud’s average. Thus, once the global collapse begins, the local clumps may complete their collapses earlier than the bulk of the cloud. They can thus begin forming stars that can begin their feedback action on the GMC before it completes the bulk collapse.

In this paper, we present numerical simulations aimed at investigating this scenario, in which we use the same cloud-formation setup of previous papers

² Zuckerman & Evans (1974) referred to these motions as “local”, and explicitly discarded large-scale coherent motions such as gravitational contraction.

(Vázquez-Semadeni et al. 2007; Banerjee et al. 2009), but including a prescription for stellar feedback mimicking ionization heating from massive stars. With this tool, we investigate the effect of the feedback on the global SFE of the evolving GMC, as well as the nature of the motions in the cloud, in a first effort to shed light on these issues. As we shall see, it turns out that the physical conditions in the clouds differ significantly from the “normal” picture, since accretion of gas from the warm diffuse medium is an integral part of the clouds’ dynamics and evolution, and thus the clouds cannot be considered as isolated.

The plan of the paper is as follows. In §2 we describe the numerical code, and the implementation of our star formation and stellar feedback prescriptions. In §3 we describe the simulations, and in §4 we describe the results concerning the control of the SFE by stellar feedback and the nature of the “clouds” themselves. Finally, in §6 we present a summary and some conclusions.

2. THE NUMERICAL MODEL

2.1. Heating and cooling

The numerical simulations used in this work were performed using the hydrodynamics + N-body Adaptive Refinement Tree code ART (Kravtsov et al. 1997; Kravtsov 2003). Among the physical processes implemented in ART, relevant for our physical problem, are the radiative heating and cooling of the gas, its conversion into stars, ionization-like heating from stellar feedback, and self-gravity, from both the stars and the gas.

We use heating (Γ) and cooling (Λ) functions of the form

$$\Gamma = 2.0 \times 10^{-26} \text{ erg s}^{-1} \quad (1)$$

$$\frac{\Lambda(T)}{\Gamma} = 10^7 \exp\left(\frac{-1.184 \times 10^5}{T + 1000}\right) + 1.4 \times 10^{-2} \sqrt{T} \exp\left(\frac{-92}{T}\right) \text{ cm}^3. \quad (2)$$

These functions are fits to the various heating and cooling processes considered by Koyama & Inutsuka (2000), as given by equation (4) of Koyama & Inutsuka (2002). As noted in Vázquez-Semadeni et al. (2007, hereafter Paper I), eq. (4) in Koyama & Inutsuka (2002) contains two typographical errors. The form used here incorporates the necessary corrections, kindly provided by H. Koyama (2007, private communication). With these heating and cooling laws, the gas is thermally unstable in the density range $1 \lesssim n \lesssim 10 \text{ cm}^{-3}$ (cf. Paper I).

2.2. Star formation and stellar feedback prescriptions

In ART, star formation is modeled as taking place in the coldest and densest regions, defined by $T < T_{\text{SF}}$ and $n > n_{\text{SF}}$, where T and n are the local temperature and number density of the gas, respectively, and n_{SF} and T_{SF} are respectively a density and a temperature threshold. We set $T_{\text{SF}} = 9000 \text{ K}$, which is easily satisfied by all cells with density n_{SF} , so in practice our SF condition depends on density only.

A stellar particle of mass m_* is placed in a grid cell where these conditions are simultaneously satisfied, and

this mass is removed from the gas mass in the cell. Thereafter, the particle is treated as non-collisional, and follows N-body dynamics. No other criteria are imposed. In each gas cell that satisfies the above criteria a stellar particle is formed with a mass equal to 50% of the gas mass contained in the cell. Since the stellar particles are more massive than a single star, each stellar particle should be considered as a small cluster, within which the individual stellar masses are distributed according to some stellar initial mass function (IMF).

Stellar particles inject thermal energy at a rate \dot{E} erg Myr^{-1} per star with mass greater than $8 M_{\odot}$ contained in the stellar particle. We assume a Miller & Scalo (1979) IMF, implying that each stellar particle of mass $133 M_{\odot}$ produces one $8 M_{\odot}$ star. The energy is deposited in the cell in which the stellar particle is instantaneously located, over a typical OB stellar lifetime, which we assume to be 10 Myr.

It is important to note that, although initially we experimented with realistic values of \dot{E} based on the Lyman continuum fluxes of stars with masses between 10 and $20 M_{\odot}$ (e.g., Diaz-Miller et al. 1998), we found that, because all the energy is deposited in a single cell, and the neighboring cells are heated exclusively by conduction, rather than by radiative heating, the resulting HII regions were not so realistic. Thus, we opted instead for taking \dot{E} as a free parameter, and adjusting it until we obtained realistic HII regions, with temperatures $\sim 10^4$ K, diameters of a few parsecs, and expansion velocities of a few tens of km s^{-1} .

Note also that we resort to the common strategy of turning off the cooling in the cell where a stellar particle is located, so that the cell can reach realistically high temperatures. Otherwise, the cooling can dissipate most of the thermal energy deposited in very dense cells. In the real ISM this does not occur because the stellar heating is applied through ionization, so that the temperature reached in the star’s immediate environment is independent of the medium’s local density. Instead, in the simulations, the cooling depends on the density, and the temperature resulting from the balance between the stellar heating and the cooling does depend on the density. This problem is avoided by turning off the cooling in the cell where the stellar particle is located. Note that this contradicts claims that the need to turn off the cooling can be alleviated simply by increasing the resolution (e.g., Ceverino & Klypin 2009). We argue that this problem can only be alleviated by performing radiation-hydrodynamics simulations. In their absence, we consider that turning off the cooling is actually a *better* model of the effect of stellar feedback, because it allows mimicking the fact that the gas temperature in the HII regions is independent of the local density.

Finally, in order to further constrain the physical conditions in the HII regions, we also impose a “ceiling” to the temperature in the cell containing the stellar particle because otherwise, with the cooling off, the temperature in the cell might diverge. We set this “ceiling” to 10^6 K.

Although this procedure is mostly one of trial-and-error, we consider it to be the most adequate one for our purposes, since it is the HII regions that drive the turbulent motions in the dense gas in our simulations, and so it is them that must have realistic properties, even at

the expense of a somewhat ad-hoc SF prescription. We show a typical HII region in our simulation in Fig. 1.

2.3. Refinement

The numerical box is initially covered by a grid of 128^3 (zeroth level) cells. The mesh is subsequently refined as the matter distribution evolves. The maximum allowed refinement level was set to four, so that high-density regions have an effective resolution of 2048^3 cells, with a minimum cell size of 0.125 pc. Cells are refined (halved in linear size) if the gas mass within the cell is greater than $0.32 M_{\odot}$. That is, the cell is refined by a factor of 2 when the density increases by a factor of 8, so that, while refinement is active, the grid cell size Δx scales with density n as $\Delta x \propto n^{-1/3}$. Once the maximum refinement level is reached, no further refinement is performed, and the cell’s mass can reach much larger values. In particular, a stellar particle is formed when a fourth-level cell reaches a density $n_{\text{SF}} = 4 \times 10^6 \text{ cm}^{-3}$, or a mass of $243.5 M_{\odot}$, again assuming $\mu = 1.27$ (we use this value because we do not follow the actual chemistry, and thus we assume the entire box to be filled with atomic hydrogen.) Thus, a stellar particle typically has a mass $\gtrsim 122 M_{\odot}$.

Note that, because we use only four levels of refinement, the largest densities arising in the simulation are by far not sufficiently resolved according to the “Jeans criterion” proposed by Truelove et al. (1997) for adaptive-mesh codes. Specifically, at our stellar-particle formation threshold density of $4 \times 10^6 \text{ cm}^{-3}$, and assuming a gas temperature of $T \sim 15$ K at that density, we find that the Jeans length (using the adiabatic sound speed) is ~ 0.031 pc, while the minimum cell size, at 0.125 pc, is roughly 4 times larger. Thus, according to those authors, one should expect artificial fragmentation to occur in our simulations. However, we do not consider this to be a problem because we are not concerned here with the numbers and masses of the stellar particles formed in the simulation, but simply with the *total* amount of mass that goes into stars.

3. THE SIMULATIONS

We consider four simulations using the same setup as in Paper I, which represents the evolution of a region of 256 pc per side, initially filled with warm gas at a uniform density of $n_0 = 1 \text{ cm}^{-3}$ and a temperature $T_0 = 5000$ K, implying an adiabatic sound speed $c_s = 7.4 \text{ km s}^{-1}$ (assuming a mean particle mass $\mu = 1.27$). The whole numerical box thus contains $5.25 \times 10^5 M_{\odot}$. In this medium, we set up two streams moving with the same speed $v_{\text{inf}} = 5.9 \text{ km s}^{-1}$ (corresponding to a Mach number of 0.8 with respect to the unperturbed medium) in opposite senses along the x -direction. The streams have a radius of 32 pc and a length of 112 pc each, so that the total mass in the two inflows is $2.25 \times 10^4 M_{\odot}$. The flows collide head on at the box’s center (see Fig. 1 of Paper I). To the inflow velocity field we superpose a field of initial low-amplitude turbulent velocity fluctuations, in order to trigger the instabilities in the compressed layer. We create this initial velocity fluctuation field with a new version of the spectral code used in Vazquez-Semadeni et al. (1995) and Passot et al. (1995), modified to run in parallel in shared-memory architectures. The simulations are evolved for about 40 Myr.

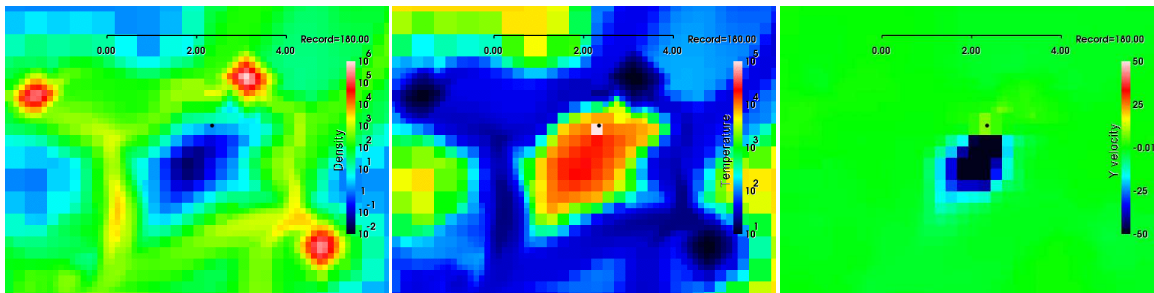


FIG. 1.— Cross sections of the density (*left panel*), temperature (*middle panel*) and y -speed (*right panel*), shown on the x - z plane, of a typical isolated HII region. The scale bar near the top indicates length in parsecs.

TABLE 1
RUN PARAMETERS

Run name	v_{rms} [km s $^{-1}$]	Feedback
LAF0	1.7	off
LAF1	1.7	on
SAF0	0.1	off
SAF1	0.1	on

The collision nonlinearly triggers a transition to the cold phase, forming a turbulent, cold, dense cloud (Audit & Hennebelle 2005; Heitsch et al. 2005; Heitsch et al 2006; Vázquez-Semadeni et al. 2006), consisting of a complex network of sheets, filaments, and clumps of cold gas embedded in a warm diffuse substrate (Audit & Hennebelle 2005; Hennebelle & Inutsuka 2006; Hennebelle & Audit 2007). The largest cold structures may become gravitationally unstable and begin to collapse. Eventually, they proceed to forming stars, which then heat their environment, forming expanding “HII regions” that tend to disperse the clumps.

In the simulations reported here, we vary only two parameters: the amplitude of the initial velocity fluctuations and whether the stellar feedback is on or off. We consider a “large-amplitude” (LA) and a “small-amplitude” (SA) case for the initial velocity fluctuations, for which the three-dimensional velocity dispersions are $v_{\text{rms}} \sim 1.7 \text{ km s}^{-1}$ and $v_{\text{rms}} \sim 0.1 \text{ km s}^{-1}$, respectively. We thus employ a mnemonic nomenclature for the runs using the acronyms LA or SA, followed by F0 or F1, indicating that feedback is off or on, respectively. Table 1 summarizes the runs considered in the paper.

4. RESULTS

4.1. Evolution of the simulations

The simulations performed here behave very similarly to previous simulations with similar setups, performed with other codes. In particular, our SA runs are very similar to run L256 Δv 0.17 in Paper I and the run presented by Banerjee et al. (2009). The main feature of these runs is that, because the initial fluctuations are very mild, the flow collision creates a large, coherent “pancake” of cold, dense gas, which is able to undergo gravitational collapse as a whole. This results in the formation of a dense, massive, and turbulent region at the site where the global collapse finally converges, with physical properties similar to those of high-mass star forming regions (Vázquez-Semadeni et al. 2009). However, a recent study varying the parameters of the flow

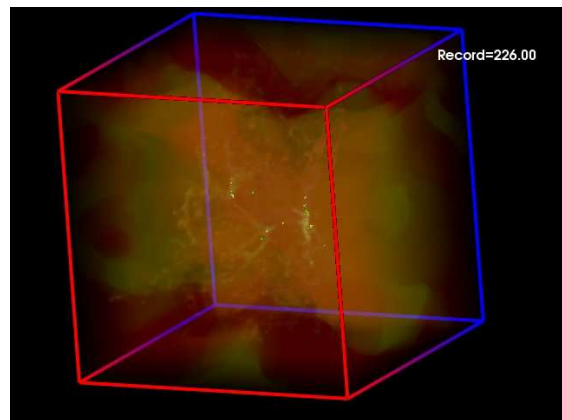


FIG. 2.— View in projection of the whole numerical box for simulation LAF1 at $t \approx 31.64 \text{ Myr}$. The box size is 256 pc. The green dots indicate stellar particles. The light yellow spots are transient dense cores, highlighted by saturation of the color table. In the electronic version, this figure shows an animation of the entire evolution of the simulation up to $t = 40 \text{ Myr}$. Records are spaced by a time interval $\Delta t \approx 0.14 \text{ Myr}$.

collision (Rosas-Guevara et al. 2010) shows that the coherence of the collapse may be lost in the presence of stronger initial velocity fluctuations, and the SFE is decreased. In such cases, smaller clouds appeared to be less strongly gravitationally bound, with the effect of decreasing the SFE. This feature also happens in our LA simulations, in which the cloud formed by the initial flow was much more fragmented and scattered over the simulation volume. As a result, SF also occurs in a much more scattered manner, and the SFEs are in general smaller in the LA runs than in their SA counterparts.

However, in general a common pattern is followed by all simulations: the transonic converging flows in the diffuse gas induce a phase transition to the cold phase of the atomic gas, which is highly prone to gravitational instability. This can be seen as follows. The thermal pressure at our initial conditions is 5000 K cm^{-3} . From Fig. 2 of Paper I, it can be seen that the thermal balance conditions of the cold medium at that pressure are $n \sim 130 \text{ cm}^{-3}$, $T \sim 40 \text{ K}$. At these values, the Jeans length and mass are $\sim 7 \text{ pc}$ and $\sim 640 M_{\odot}$, respectively. These sizes and masses are easily achievable by a large fraction of the cold gas structures, which can then proceed to gravitational collapse and form stars. Moreover, the ensemble of these clumps may also be gravitationally unstable as a whole, the likelihood of this being larger for greater coherence of the large-scale pattern.

Regions of active star formation form in both sets of simulations by the gravitational merging of pre-existing

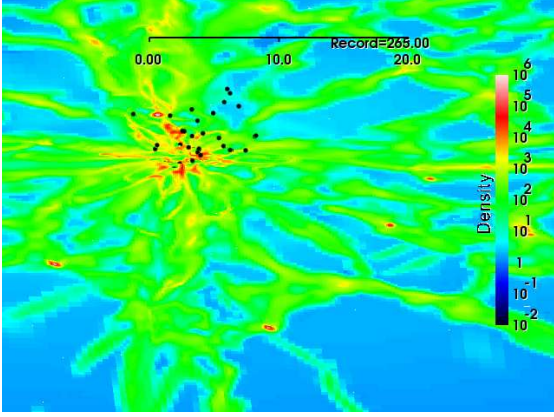


FIG. 3.— Cross-section view through the Central Cloud in run SAF1 at $t \approx 33$ Myr, at which time it has grown to a mass of $\sim 3 \times 10^4 M_\odot$. The plane of the image is shown from an inclined line of sight for better perspective. The cloud is seen to contain numerous HII regions mixed with dense regions. In the electronic version, this figure shows an animation of the build-up of this cloud, illustrating how it forms by the continued accretion of infalling material from the globally collapsing GMC. In the animation, note that many of the infalling clumps form stellar particles before reaching the center, and are disrupted by the local stellar feedback. However, once the Central Cloud is fully assembled, it resists dispersal, and forms stars at a high rate.

smaller-scale clumps, which, altogether, form a larger-scale GMC. Figure 2 shows a whole-box image of the density field in run LAF1, in projection. In the electronic version of the paper, this figure shows an animation of this run from $t = 0$ to $t \approx 40$ Myr, illustrating the entire evolution of the simulation, from the assembly of the cloud, to its advanced star-forming epochs. In the animation, subsequent “records” are separated by time intervals $\Delta t \approx 0.14$ Myr.

In the SA runs, the largest star-forming region forms in the center of the simulation, due to the coherent collapse of the entire sheet-like cloud formed by the collision. This was the region shown in Vázquez-Semadeni et al. (2009) to exhibit physical conditions typical of actual high-mass star-forming regions. We refer to this region as “the Central Cloud”. Figure 3 shows a view of this region at $t \approx 33$ Myr, a time at which the central cloud has grown to a mass of nearly $3 \times 10^4 M_\odot$ in run SAF1 (cf. Fig. 5). In the case of the LA runs, because star formation occurs in a much more scattered fashion, we study two of the regions exhibiting the strongest star formation activity, neither of which is located at the center of the numerical box. These are shown in Fig. 4, and we refer to them as Cloud 1 and Cloud 2.

4.2. Effect of stellar feedback on the SFE and on the clouds’ evolution

Our main interest in this contribution is the effect of the feedback on the efficiency of the star formation process, and the identification of the mechanism through which this effect is accomplished. Figure 5 shows the evolution of the dense gas mass and the stellar mass in these simulations, with (right panels) and without (left panels) feedback. The solid lines refer to the total masses in the computational box, while the dotted lines refer to the masses in the Central Cloud. Figures 6 and 7 show the corresponding plots for Cloud 1 and Cloud 2. Here, the solid lines represent the masses for the full simulation

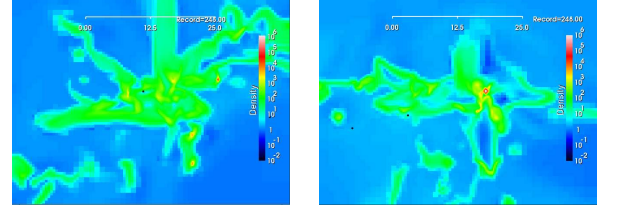


FIG. 4.— Cross-section view through Clouds 1 (top panel) and 2 (bottom panel) at $t \sim 35$ Myr in simulation LAF1. The plane of view is located at $x = 100$ pc for Cloud 1 and at $x = 150$ pc for Cloud 2. The dots represent the stellar particles. In the electronic edition, these figures show animations of the evolution of both clouds from $t = 23$ to $t = 40$ Myr.

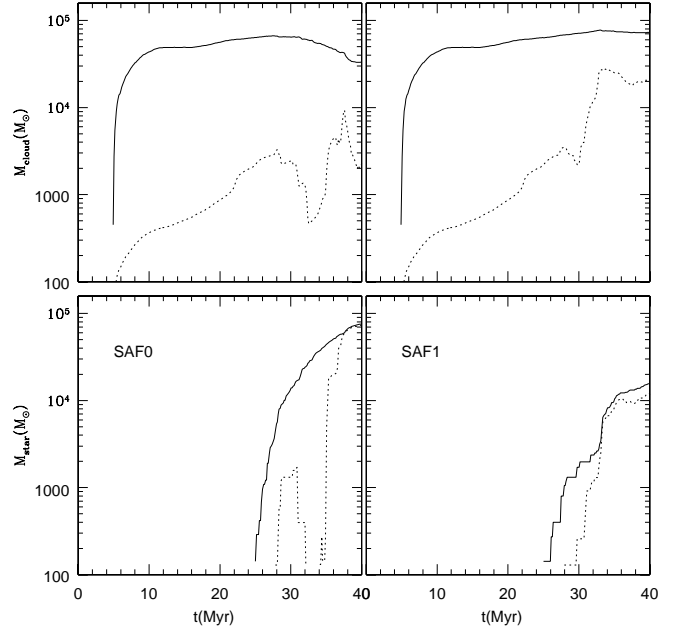


FIG. 5.— Evolution of the dense gas mass and the stellar mass for the SA simulations, without (left panels, run SAF0) and with (right panels, run SAF1) feedback. The solid lines refer to the total masses in the computational box, while the dotted lines refer to the masses in a cylinder with length and diameter of 10 parsecs with its axis along the x -direction, and which contains the Central Cloud.

box, and the dotted, short-dashed, and long-dashed lines represent the masses contained in cylinders of length and diameter 10, 20, and 30 pc, respectively, enclosing the clouds. We do this because the clouds have very complicated morphologies, with filaments that extend out over tens of parsecs and connecting with other clouds (Fig. 4), thus making it virtually impossible to fully enclose the “clouds” in any given cylindrical volume.

It is seen from Figs. 5-7 that the inclusion of feedback (right panels) causes the dense gas mass to be larger and the stellar mass to be smaller than in the case without feedback in general, even though the total cloud mass (dense gas + stars) in the simulations is nearly the same in both the cases with and without feedback (Fig. 8). As a consequence, the instantaneous SFE, defined as

$$\text{SFE}(t) = \frac{M_*(t)}{M_{\text{dense}}(t) + M_*(t)}, \quad (3)$$

where $M_{\text{dense}}(t)$ is the mass of the dense ($n \gtrsim 50 \text{ cm}^{-3}$)

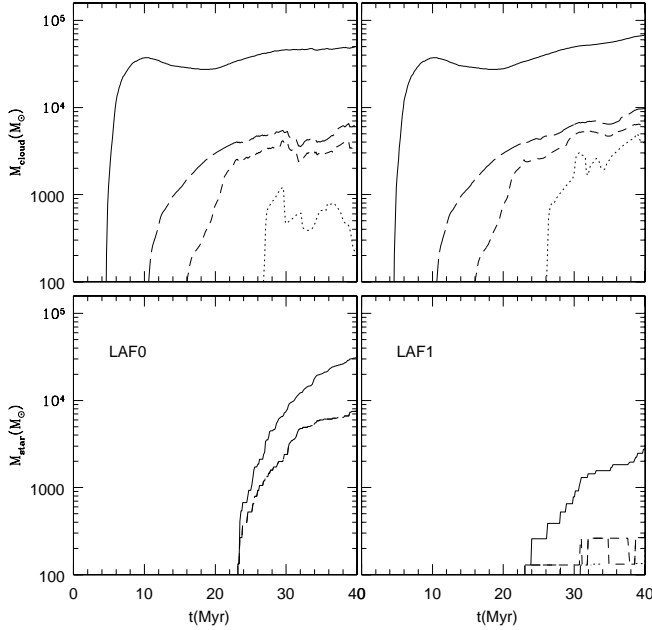


FIG. 6.— Evolution of the dense gas mass and the stellar mass for Cloud 1 in the LA simulations, without (*left panels*) and with (*right panels*) feedback. The *solid* lines refer to the total masses in the computational box. The other lines refer to the masses in cylinders of length and diameter 10 pc (*dotted lines*), 20 pc (*short-dashed lines*), and 30 pc (*long-dashed lines*).

gas in the simulation, and $M_*(t)$ is the stellar mass, naturally decreases upon the inclusion of feedback in both sets of simulations (Fig. 9). Note that in eq. (3) we have explicitly written out the time dependence of the quantities involved.

The SFE is seen to be reduced by a larger factor ($\sim 10\times$) in the case of the LA runs, in which the collapse is less focused and less massive, than in the case of the SA ones ($\sim 3\times$), in which the opposite is true. In addition, in Fig. 10 we show the evolution of the SFE at the level of the clouds. The *left panel* shows the evolution of the SFE for the Central Cloud in the SA runs. The *middle panels* show the corresponding plots for Cloud 1 and Cloud 2 in the LAF0 run (without feedback), and the *right panels* show the SFEs in the LAF1 run (with feedback). Again we see a trend for the less massive cloud (Cloud 1) to suffer a greater reduction of its SFE (by a factor of ~ 20 , from ~ 60 -90% to ~ 3 -4%) than the more massive one (Cloud 2, by a factor of ~ 10 , from ~ 70 -80% to ~ 7 -8%). We discuss the possible causes for this mass-dependent effect of the feedback in Sec. 4.3.2.

The factor by which the SFE is reduced upon the inclusion of the feedback in the simulations is plotted versus the system's mass in Fig. 11, both for the full amount of dense gas in the simulations, and for each of the clouds we have been considering. We see that two sets of points are clearly defined in this plot, one for the clouds, and one for the simulations. In both cases, however, the trend of larger reduction factor at smaller dense gas mass is clearly observed, although, at the level of simulations, we see that their masses are not very different. Thus, in this case the different reduction factors must include a contribution from the larger degree of fragmentation occurring in the LA simulations due to the larger am-

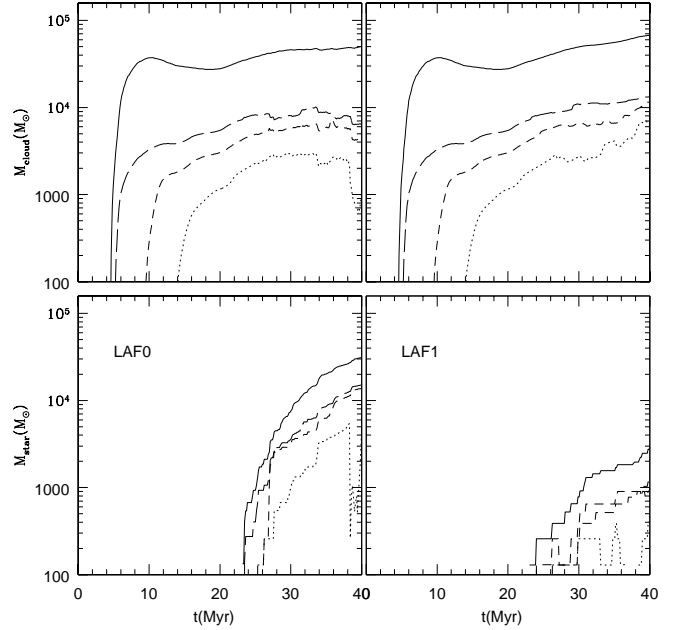


FIG. 7.— Evolution of the dense gas mass and the stellar mass for Cloud 2 in the LA simulations, without (*left panels*) and with (*right panels*) feedback. The *solid* lines refer to the total masses in the computational box. The other lines refer to the masses in cylinders of length and diameter 10 pc (*dotted lines*), 20 pc (*short-dashed lines*), and 30 pc (*long-dashed lines*).

plitude of the initial turbulent fluctuations. beginfigure

In order to compare the SFEs in our simulated clouds with those of real molecular clouds, it is convenient to note that regions of low-mass star formation, such as Taurus (Goldsmith et al. 2008) or the Chamaeleon II dark cloud (Spezzi et al. 2008) generally have low SFEs (~ 1 -5%), while cluster forming cores have SFE ~ 30 -50% (Lada & Lada 2003). Thus, we can check whether the SFEs and SFRs of our three clouds follow the same trend. Figure 12 shows the evolution of the SFRs for our three clouds. From these plots, we find that the average SFR of the Central Cloud starting from $t = 32$ Myr (the time at which a large, roughly stationary SFR sets in) is $\langle \text{SFR} \rangle \sim 1450 M_\odot \text{ Myr}^{-1}$, while for Clouds 1 and 2, we find $\langle \text{SFR} \rangle \sim 30$ and $60 M_\odot \text{ Myr}^{-1}$ during their entire star-forming stages, respectively. From here, and using the instantaneous SFE at $t = 40$ Myr from Fig. 10, we can then plot the SFE *versus* the SFR. This is shown in Fig. 13, in which both the SFR and the SFE have been multiplied by an extra factor of 0.5, to represent the fact that the efficiency within the stellar particles, which are created at a density of $n = 4 \times 10^6 \text{ cm}^{-3}$ in our simulations, is still smaller than unity. We take 0.5 as a representative value.

We see that the Central Cloud has values of the SFR and the SFE comparable to those of cluster-forming cores (Lada & Lada 2003). Specifically, Vázquez-Semadeni et al. (2009) estimated an $\text{SFR} \gtrsim 250 M_\odot \text{ Myr}^{-1}$ for the Orion Nebula Cluster (ONC). This calculation used an estimated age spread of the ONC of $\lesssim 2$ Myr (Hillenbrand 1997), and Tobin et al. (2009)'s result of there being 1613 stars in the ONC.

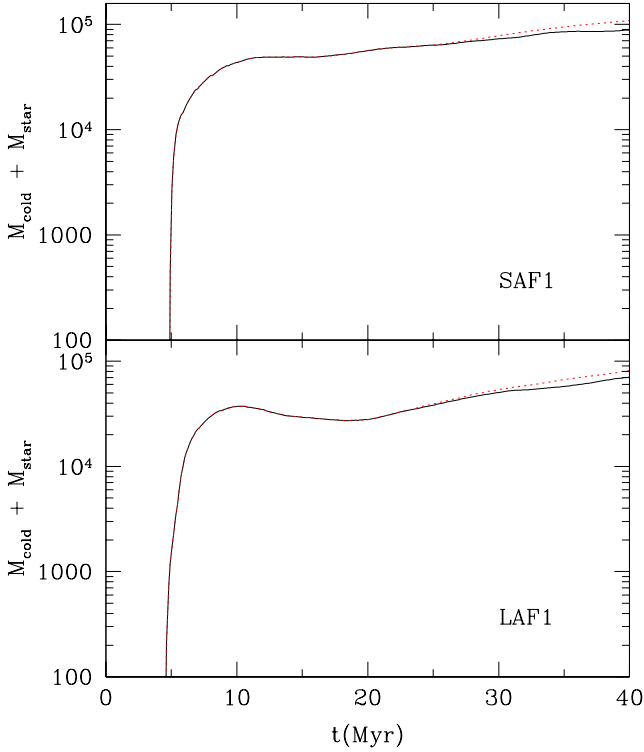


FIG. 8.— Evolution of the total (dense gas + stars) mass for the four simulations. The SA simulations are shown in the *top panel*, while the LA runs are shown in the *bottom panel*. The *black, solid* lines refer to simulations with feedback and the *red, dotted* lines represent runs without it. The colors are shown in the electronic version only.

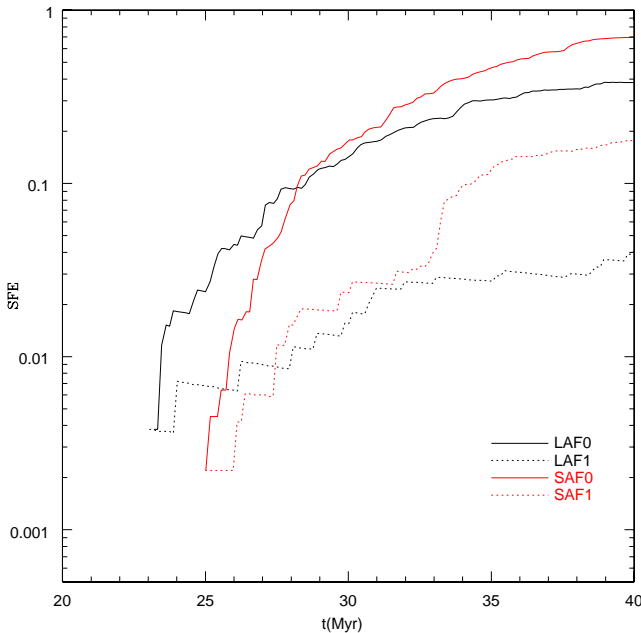


FIG. 9.— Evolution of the instantaneous star formation efficiency (SFE), as defined in eq. (3), in the full simulation box in the four runs.

Taking this number as a proxy for the total stellar production of this region, and a mean stellar mass of $0.3 M_{\odot}$ (Hillenbrand & Carpenter 2000), this implied a total stellar mass of $\sim 500 M_{\odot}$. On the other hand, Krumholz & Tan (2007) quote a total stellar mass in the ONC of $\sim 4600 M_{\odot}$ (Hillenbrand & Hartmann 1998) and an age spread of ~ 3 Myr (Tan et al. 2006), implying an $\text{SFR} \sim 1530 M_{\odot} \text{ Myr}^{-1}$. These values bracket the SFR we measured for our Central Cloud.

Concerning the SFE, Fig. 13 shows that the Central Cloud has $\text{SFE} \sim 10\%$, which is comparable to that of the Orion A cloud (Carpenter 2000), in which the OMC-1 clump is contained. Thus, our Central Cloud may be compared to the Orion A cloud, and its dense core, discussed in Vázquez-Semadeni et al. (2009), is comparable to the OMC-1 clump.

On the other hand, Clouds 1 and 2 are seen in Fig. 13 to have SFRs comparable to those of low-mass star-forming clouds, $\sim 10\text{--}100 M_{\odot} \text{ Myr}^{-1}$, such as Taurus, Cha II or Lupus, in which the SFE is known to be lower, $\sim 1\text{--}4\%$ (Spezzi et al. 2008). This compares very well with the SFEs we report for our Clouds 1 and 2 in the same figure. We conclude that Clouds 1 and 2 are good models of low-mass star-forming regions, while the Central Cloud is a good model of a massive SF region, as discussed in Vázquez-Semadeni et al. (2009).

4.3. The physical processes acting on the clouds

4.3.1. Cloud “destruction”

Up to the 40-Myr time to which we have evolved our simulations, the three large clouds (the Central Cloud in run SAF1 and Clouds 1 and 2 in run LAF1) do not show any instances of the dense gas mass reversing its increasing trend and beginning to decrease due to the feedback, as can be seen in Figs. 5 through 7. Apparently, the HII region-like feedback we use is unable to overwhelm the large gravitational potential well of these clouds and their enveloping “atomic” gas reservoirs.

Instead, complete destruction seems to be able to occur in small clumps. This can be seen in the animation corresponding to Fig. 3, in which various small clumps are seen to be destroyed by their stellar products. Three particularly conspicuous ones are, first, the one that forms a stellar particle at the very starting frame (record 179) of the animation, slightly above and to the right of the screen’s center. Next, another stellar particle appears in the clump almost at the left border of the frame, about 2/3 of the way from bottom to top, at record 187. Finally, a third particle appears at record 189, slightly below and to the right of the screen’s center, as the result of the collision of two clumps. In all of these cases, a single stellar particle is formed ($\sim 120 M_{\odot}$), and the clump is destroyed. It is worth noting that actually, the expansion of the HII regions formed produces new clumps from the material collected around it, but these new clumps either disperse, or simply do not form new stars.

Thus, we conclude, similarly to Krumholz, Matzner, & McKee (2006), that small clouds (“clumps”) are rapidly destroyed, while large clouds may survive for longer times. However, our clouds exhibit a fundamental difference with respect to the model considered by those authors, namely that the clouds are accreting in general. In the next section we

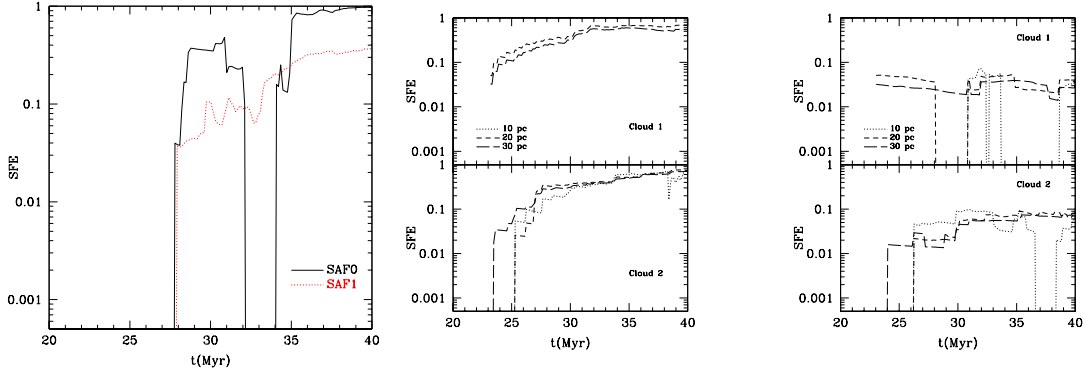


FIG. 10.— Evolution of the instantaneous star formation efficiency (SFE) in the dense clouds in the simulations. The *left panel* shows the SFE for the Central Cloud of the SA runs, with and without feedback. The measurements refer to a cylindrical box with a diameter and a length of 10 pc. The *middle panels* show the SFE for Clouds 1 and 2 in the LAF0 simulation (without feedback), for three different cylindrical boxes, of length and diameter indicated in the labels. The gaps in the curves for the smaller cylindrical boxes correspond to times when the stellar particles migrate out of them, and no new particles have been formed. The *right panels* show the SFE for Clouds 1 and 2 in the LAF1 simulation (with feedback).

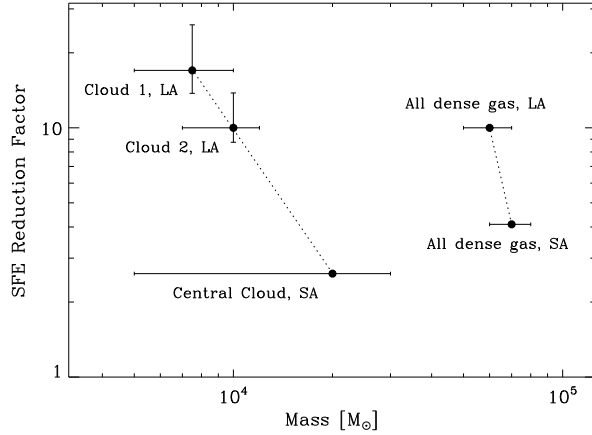


FIG. 11.— Reduction factor of the SFE at 40 Myr upon inclusion of the feedback in the simulations, both for the three clouds as well as for the entire mass of dense gas in the simulations. The error bars in the masses indicate the range of values taken by the systems once their initial assembly has finished (see Figs. 5-7). The error bars in the reduction factor for Clouds 1 and 2 denote the maximum and minimum values of the ratio $\text{SFE}(\text{w/o feedback})/\text{SFE}(\text{w/feedback})$, using the SFE data for the three cylinder sizes of 10, 20 and 30 pc.

now discuss this feature.

4.3.2. Accretion vs. feedback

One crucial feature in all our simulations is that *the clouds are accreting material from the surrounding diffuse medium*. This is fundamentally different from models in which the clouds are isolated entities, in rough balance between their self-gravity and the turbulent pressure, possibly driven by the stellar feedback. The accretion competes with SF and stellar feedback in regulating the cloud’s mass and coherence, with important consequences. First of all, this implies that simple observational estimates of the SFE in GMCs based on measuring the stellar mass and dividing it by the cloud’s mass may be failing to take into account the additional “raw material” for SF contained in the part (or the whole) of the atomic envelope of the clouds that will eventually be incorporated into the GMC.

Second, the competition between feedback and accre-

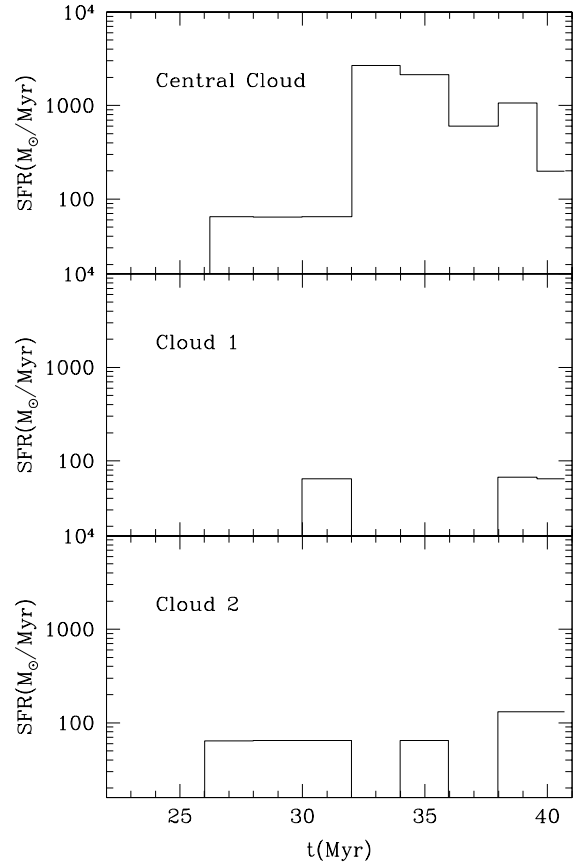


FIG. 12.— Evolution of the stellar particle formation rate, averaged over 2-Myr intervals, of the Central Cloud (*top panel*), Cloud 1 (*middle panel*) and Cloud 2 (*bottom panel*). For this plot we only use the 10-pc cylindrical volumes for Clouds 1 and 2. Because our stellar particles form at a density of $n = 4 \times 10^6 \text{ cm}^{-3}$, actual star formation rates should be a factor of 2-3 lower. Gaps indicate periods over which no new stars are formed.

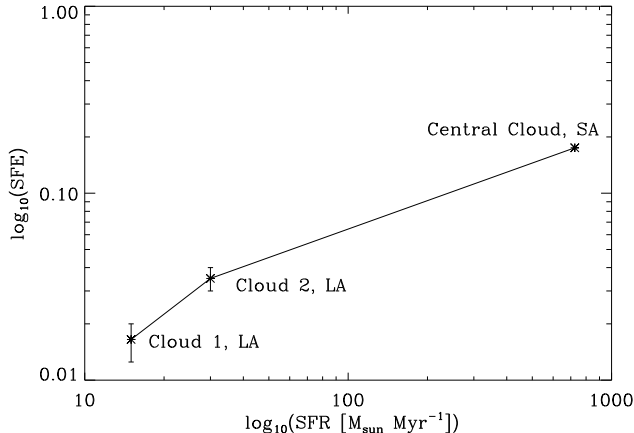


FIG. 13.— SFE *versus* stellar-particle formation rate for the three clouds in the simulations, using the data from Figs. 10 and 12. The values of both the SFR and the SFE have been multiplied by a factor of 0.5, representative of the still-lower-than-unity efficiency within our stellar particles.

tion may explain our observation from Sec. 4.2 that cases with feedback are characterized by *larger* dense gas masses and smaller stellar masses than their counterparts without feedback. The smaller stellar mass is not surprising, as the obvious effect of stellar feedback is to reheat the cold, collapsing star-forming gas, thus reducing the SFR. However, the larger cold gas mass in the presence of feedback is indeed surprising, since both gas consumption by SF and the “ionization” by stellar feedback act to reduce the dense gas mass. Our result implies that the rate of dense gas consumption by SF far outweighs its rate of destruction by stellar feedback, so that the net effect of reducing the SFR is to allow a larger amount of dense gas to be collected by the accretion. This scenario is supported by Fig. 8, which shows the total (dense gas + stars) in the clouds in the two sets of simulations. It is seen that the total cloud mass is nearly the same with and without feedback, suggesting that *the total cloud mass is mainly determined by the accretion, while the ratio of dense gas to stellar mass seems to be mainly determined by the feedback.*

These results moreover support the suggestions by Elmegreen (2007) and Vázquez-Semadeni et al. (2009) that the majority of the gas in a GMC is not participating of the SF process at any given time. The latter authors suggested that this is how local regions of SF may have a very high specific SFR ($\sim (10 \text{ Myr})^{-1}$), while that of their whole parent GMCs may be much smaller ($\sim (300 \text{ Myr})^{-1}$; McKee & Williams 1997). Because it is injected by the newly formed stars, the stellar feedback acts preferentially on gas that is about to form stars next. This allows an efficient suppression of SF, through only a modest fraction of the total available dense gas being destroyed. That is, if SF is a highly localized process, then it is possible to achieve significant reductions of the SFR with only a modest reduction of the total amount of dense gas, by targeting the destruction precisely at the star-forming gas.

This mechanism may also explain the trend observed in Sec. 4.2, that the SFE is more strongly reduced by the feedback in cases where the collapsing gas mass is smaller. This may be understood as a consequence of the

fact that stellar feedback is localized, while the accretion is extended, and more so for greater mass of the globally gravitationally unstable region that will form the cloud. Thus, as we observe in the animation corresponding to Fig. 3, the low-mass fragments that are undergoing SF while on their way to the central site of the global collapse in run SAF1 are easily destroyed by their stellar activity. Instead, the massive Central Cloud is not destroyed, as it continues to accrete mass from large distances at a pace that outweighs the local destruction by stellar feedback. Clouds 1 and 2 in run LAF1, which do not involve such an extended collapse, are intermediate cases, in which the clouds are not destroyed by the feedback, but the latter is more efficient in reducing the SFE.

Thus, we can conclude that the efficacy of the feedback in destroying the cloud is maximal when its region of influence is comparable to the spatial extent of the infall, and is progressively reduced as the latter involves progressively larger coherence lengths.

4.4. Physical conditions in the clouds

Here we consider the global physical properties of the clouds. We postpone a discussion of the properties of individual clumps within the clouds for a future study, to be performed at higher resolution. One such study, including magnetic fields, although not including stellar feedback, has recently been presented by Banerjee et al. (2009).

4.4.1. Density PDFs

It is important to determine the physical conditions in our clouds in order to assess their degree of realism. One basic diagnostic is the probability density function (PDF) of the density field. Although it is well established that in isothermal flows the density PDF takes a lognormal form (Vázquez-Semadeni 1994; Padoan et al. 1997; Passot & Vázquez-Semadeni 1998; Nordlund & Padoan 1999; Ostriker et al. 1999, 2001; Federrath et al. 2008), for non-isothermal flows the expectation is in general different, with a near-power-law tail developing at high densities for flows softer than isothermal (Passot & Vázquez-Semadeni 1998; Scalo et al. 1998; Nordlund & Padoan 1999; Gazol et al. 2005; de Avillez & Breitschwerdt 2004, although see, e.g., Wada & Norman 2001, 2007), and a bimodal form arising for thermally bistable flows (Vázquez-Semadeni et al. 2000; Gazol et al. 2005; Audit & Hennebelle 2005, see also the review by Vázquez-Semadeni 2009).

Figure 14 shows the density PDFs for the whole simulation box of the SA runs *top panels* and of the LA runs *bottom panels*. The *right panels* show the entire density range, while the *left panels* show the PDF for the dense gas ($n \geq 100 \text{ cm}^{-3}$) only. The whole-range PDFs exhibit the bimodality typical of thermally bistable flows, although the high-density tail is seen to exhibit an excess over the power-law in both the cases with and without feedback. This is probably due to the action of self-gravity (Klessen 2000; Dib & Burkert 2005; Vázquez-Semadeni et al. 2008). In addition, the cases with feedback show a slight excess over the cases without it at densities $10^3 \lesssim n \lesssim 10^5 \text{ cm}^{-3}$, probably due to the formation of compressed regions by the expanding “HII regions”. The high-density PDFs, being just

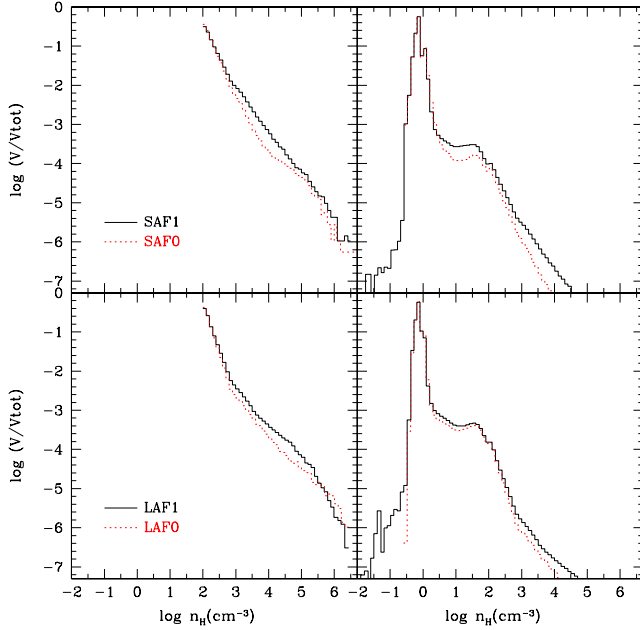


FIG. 14.— Density PDFs for the entire simulation boxes of the SA runs (*top panels*) and the LA runs (*bottom panels*). The *right panels* show the PDFs for the entire range of densities, while the *left panels* show the PDFs of the dense gas only ($n \geq 100 \text{ cm}^{-3}$). The *red, dotted lines* refer to the simulations without feedback, while the *black, solid lines* show represent the simulations with feedback.

the $n > 100 \text{ cm}^{-3}$ tail of the whole-range PDFs, only show more detail of the very-high density gas, up to the star-forming density of $4 \times 10^6 \text{ cm}^{-3}$, but with the same shape of the curves as in the whole-range PDFs.

In order to see the PDFs at the locations of the three main clouds we have studied (the Central Cloud in the SA runs and Clouds 1 and 2 in the LA runs), we show in Fig. 15 their corresponding density PDFs. It is noteworthy that the PDFs again show a roughly power-law shape at high densities over three to four orders of magnitude in density, in agreement with the expectation for softer-than-isothermal flows (Passot & Vázquez-Semadeni 1998; Nordlund & Padoan 1999). This is at odds with results from numerical simulations of turbulent isothermal gas in closed boxes, but then again our clouds are *not* isothermal. Instead, they are characterized by an effective polytropic equation of state $P \propto \rho_{\text{eff}}^{\gamma}$, with γ_{eff} varying from 0.8 to nearly unity for $n \gtrsim 100 \text{ cm}^{-3}$, as can be seen in Fig. 16. Real interstellar molecular gas is not expected to be exactly isothermal, either (Scalo et al. 1998; Spaans & Silk 2000; Jappsen et al. 2005). Moreover, our clouds are immersed in a diffuse, warmer medium which, as proposed, e.g., by Li & Goldsmith (2003) and Hennebelle & Inutsuka (2006), infiltrates the clouds to some degree. Thus, the density PDFs for the volumes containing our clouds also exhibit the bimodal shape characteristic of thermally bistable flows, and have low-density tails that extend down to the WNM regime, contrary to what happens in isothermal simulations.

4.4.2. Velocity dispersions and virial masses

Finally, we investigate the global velocity dispersion (Δ_v) in the Central Cloud and Clouds 1 and 2. This

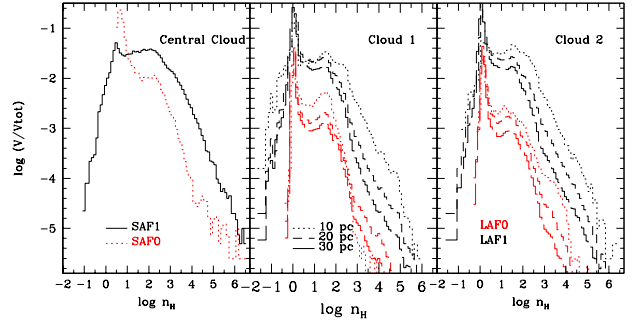


FIG. 15.— Density PDFs for the three main clouds in the simulations: the Central Cloud in the SA runs (*left panel*), and Clouds 1 (*middle panel*) and 2 (*right panel*) in the LA runs. The PDFs for the Central Cloud are computed in a cylinder with length and diameter equal to 10 pc, while the PDFs for Clouds 1 and 2 are computed in cylinders of length and diameter equal to 10, 20 and 30 pc. Red lines indicate cases without feedback, and are displaced downwards by a factor of 10 for better viewing in the cases of Clouds 1 and 2. Black lines indicate cases with feedback.

is shown in Fig. 17. The *solid lines* show the density-weighted value, while the *dotted lines* show the volume weighted value. *Black lines* denote cases with feedback, and *red lines* correspond to cases without it.

For the Central Cloud and Cloud 2, which are the two most massive ones, the density-weighted velocity dispersion, which highlights the dense gas, *decreases* upon the inclusion of feedback. Without feedback, in the Central Cloud, it reaches very high values at the end of the run ($\sim 15 \text{ km s}^{-1}$, corresponding to Mach numbers $M_s \sim 50-75$), which in fact are significantly larger than typical values for cloud complexes of comparable mass ($M \gtrsim 10^4 M_\odot$; e.g., Dame et al. 1986; Rathborne et al. 2009). Instead, in the run including feedback, Δ_v reaches values $\sim 5-6 \text{ km s}^{-1}$ (rms Mach number, $M_s \sim 20$), in much better agreement with typically observed values. On the other hand, the volume-weighted velocity dispersion, which highlights the less dense gas, is seen in Fig. 17 to *increase* upon the inclusion of feedback. In Clouds 1 and 2, which are less massive and more scattered than the Central Cloud, Δ_v does not achieve exceedingly large values in any case.

These results can be understood as a consequence of the fact that the dense gas acquires its largest velocities in the case of free-fall collapse. However, the collapse flow is dismantled in its final (fastest) stages by the stellar feedback, so that it is the high-velocity dense gas that is preferentially destroyed by the feedback. On the other hand, this gas becomes warm, diffuse, high-velocity *expanding* gas, which is the one highlighted by the volume weighting. These results again reinforce the notion that

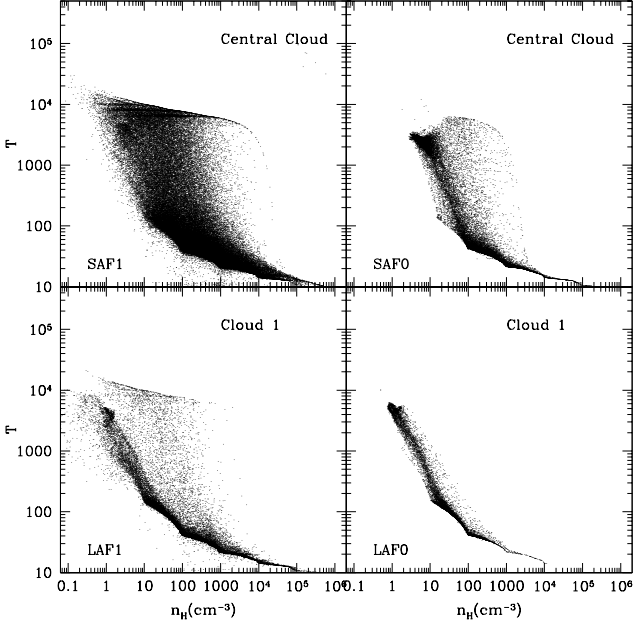


FIG. 16.— Phase-space diagrams of temperature vs. density for the Central Cloud (*left panels*), Cloud 1 (*middle panels*) and Cloud 2 (*right panels*). The *top panels* show the cases without feedback, and the *bottom panels* show the cases with feedback. It can be seen that, for the majority of the points, the temperature only varies between ~ 40 and 10 K for $100 < n < 10^6 \text{ cm}^{-3}$. The exceptions are locations recently heated by new stars.

the feedback is mostly applied on the gas that is closest (but not quite there yet) to forming stars.

Once we have determinations of the velocity dispersion in the cylinders containing the clouds, it is natural to measure the virial mass (M_{vir}) of the clouds and compare it with their real mass M , in order to check whether they look “virialized”. We compute the virial mass through the standard formula

$$M_{\text{vir}} \equiv 210 \left(\frac{R}{\text{pc}} \right) \left(\frac{\Delta v}{\text{km s}^{-1}} \right)^2 M_{\odot}, \quad (4)$$

(see, e.g., Caselli et al. 2002; Tachihara et al. 2002; Klessen et al. 2005). For the real cloud mass we consider the sum of the gas (dense + diffuse) and stellar masses in the volume being considered. It is important to note that, with this prescription, variations in the value of the ratio come exclusively from the estimate of the virial mass, because it *does* depend on the weighting used, while the actual cloud mass is independent of the method of weighting.

Figure 18 shows the evolution of the ratio M/M_{vir} for the three clouds, showing the cases with and without feedback, and using volume- and density-weighting for the calculation of Δv . In all cases we observe that, at advanced stages of the evolution, when the clouds have been fully assembled ($t \gtrsim 25$ Myr), this ratio is closest to unity when feedback is included and density-weighting is used in the calculation of Δv . The cases with no feedback and density weighting are systematically lower than unity by factors ~ 2 -10. The cases with volume weighting are more strongly fluctuating, but it is noteworthy that the ratio often takes values close to unity anyway.

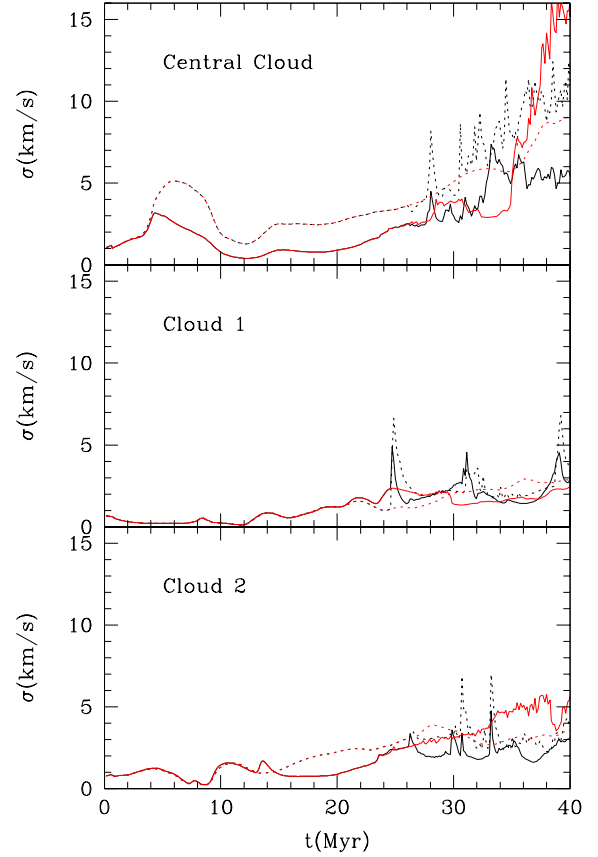


FIG. 17.— Evolution of the velocity dispersion σ in the three clouds. The *solid lines* show the density-weighted value, while the *dotted lines* show the volume weighted value. *Red lines* correspond to cases without feedback, and *black lines* correspond to cases with feedback.

From these results, we conclude that, in the case with feedback, the clouds appear to be in a pseudo-virialized state with respect to the velocity dispersion of the dense gas (highlighted by the density weighting). In this state, there is an approximate force balance between self-gravity and feedback driving. However, it differs from true virialization because of the presence of mass sources (the accretion from the diffuse environment) and sinks (the consumption by SF and the destruction by stellar feedback) in the system. These seem to self-regulate, so as to be capable of maintaining an approximately constant cloud mass while accretion persists. On the other hand, when the velocity dispersion of the warm gas is taken into account (still in the case with feedback), the clouds appear to be slightly sub-virial, suggesting that the newly formed warm gas in the HII regions is capable of escaping the cloud.

In the cases without feedback, the clouds also appear to be sub-virial even with respect to the density-weighted virial mass estimate. In this case this appears to be a consequence of the dense gas being in free-fall collapse, and into a potential well produced not only by its own self-gravity, but also by the previously-formed stars that have fallen there too (see Vázquez-Semadeni et al. 2009).

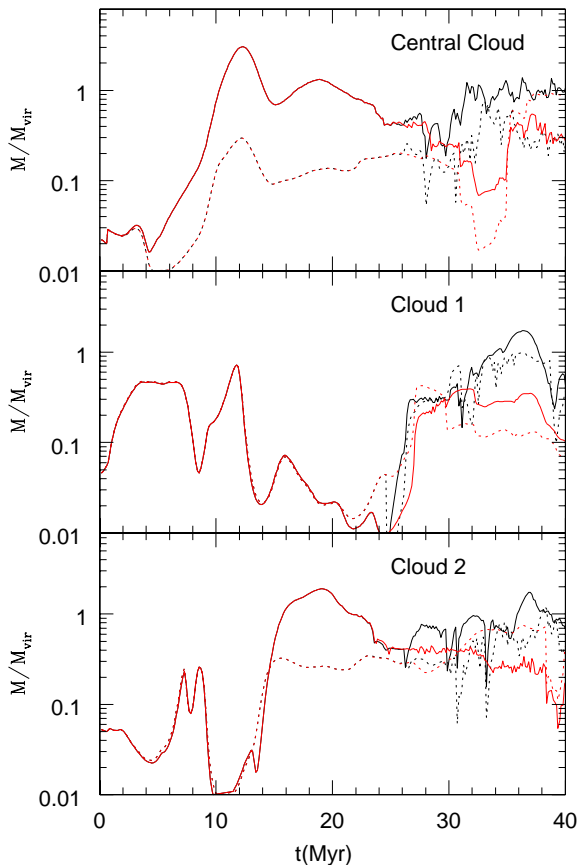


FIG. 18.— Evolution of the ratio of actual to virial mass for the three clouds. Red lines correspond to the runs without feedback. Black lines correspond to the runs with feedback. Solid lines correspond to the density-weighted velocity dispersion, while dotted lines correspond to the volume-weighted one.

5. CAVEATS AND LIMITATIONS

Of course, our simulations are not free of caveats and limitations. Two that stand out are the resolution and the nature of the feedback that we have included. Concerning the resolution, in this paper we have used a relatively limited one, in order to speed up the simulations, at the expense of not fulfilling the Jeans criterion proposed by Truelove et al. (1997). However, as explained in Sec. 2.3, we do not consider this a problem for our study, since we have restricted it to the global properties of the clouds, rather than their detailed structure, and we have avoided addressing issues related with the fragmentation of the final stages of collapse in the clouds, such as the mass distribution of the cores and stellar products. We plan to perform a higher-resolution study in a forthcoming paper, in which we can address these issues.

The second limitation is the nature of the stellar feedback that we have considered, which in this study has been restricted to local heating representing the ionizing radiation from massive stars, similarly to the approach used by, e.g., Yorke et al. (1982); Vázquez-Semadeni et al. (1995); Passot et al. (1995), neglecting other sources such as outflows from stars of all masses (e.g., Norman & Silk 1980; Li & Nakamura 2006;

Matzner 2007; Nakamura & Li 2007; Carroll et al. 2009; Wang et al. 2009). We do this in part for the numerical simplicity of the approach, and in part because here we have been mainly interested in the SFE and cloud evolution at the scale of GMCs, for which the expansion of HII regions is likely the main driver (Matzner 2002). However, the neglect of bipolar outflows may introduce a non-negligible bias in our finding that smaller-scale clumps are destroyed by the feedback, and this should be confirmed by future simulations that can better resolve these objects and include bipolar outflows.

6. SUMMARY AND CONCLUSIONS

In this paper we have presented a numerical investigation of the evolution of dense (“molecular”) clouds, starting from their formation by transonic compressions in the warm neutral medium, followed by a phase transition to the cold neutral medium, the onset of gravitational collapse, star formation, and, finally, energy feedback from massive-star ionizing radiation and the formation of expanding HII regions.

A crucial difference between the results from our simulations and other models and theories of the self-regulation of star formation and its efficiency (e.g., Whitworth 1979; Elmegreen 1983; Franco, Shore & Tenorio-Tagle 1994; McKee & Tan 2003; Krumholz & McKee 2005) is that the clouds in our simulations are in general accreting material at high rates from the surrounding diffuse medium, rather than having a fixed mass. This implies that *the material making up a cloud is constantly being renewed over time* because, on the one hand it is accreting fresh gas, and on the other it is losing mass to SF and stellar ionization. The star-forming regions can be considered to be not objects, but rather the *loci* where the gas is just “passing through”, from the diffuse-gas state to the “star” state, similarly to the nature of a flame, which is the locus of the gas undergoing combustion in a candle, with fresh air entering at its base, burning while it transits through the flame, and the exhaust gases leaving at the top.

Within this framework, we have found that the SFE in the clouds is readily decreased by feedback to levels consistent with observational determinations *at all times during the clouds’ evolution* up to the maximum integration time of 40 Myr that we have considered. This is a significant improvement over our previous non-magnetic studies of the SFE in the context of cloud evolution without feedback, in which the SFE at late times is often found to be excessive (e.g., Vázquez-Semadeni et al. 2007; Rosas-Guevara et al. 2010). However, we have found that the reduction factor upon the inclusion of feedback is an inverse function of the dense gas mass in the system, and of the degree of coherence of the global collapse, as illustrated in Fig. 11. This result is complemented by the additional observation that low-mass clumps are fully destroyed by the feedback. Together they imply that at some point, below a certain critical collapsing mass, the appearance of a stationary state may not occur anymore. This is in qualitative agreement with the results of Krumholz, Matzner, & McKee (2006), although their model does not include mass accretion onto the cloud. We plan to present one such model in a future paper.

In general, our results may provide an explanation

for the observational fact that regions of massive-star formation, which are themselves more massive than regions of low mass-star formation, appear to have higher SFEs (Lada & Lada 2003) than regions forming low- and intermediate-mass stars (Evans et al. 2009). Essentially, our results imply that *the more massive the region, the less effective the feedback is in reducing the SFE*. Specifically, these results indicate that the role of the feedback is not the same in all clouds, but rather depends on the initial conditions of the large-scale collapse that produces each individual region. Regions in which the amount of mass involved in the collapse overwhelms the destructive action of the feedback may reach a stationary state that appears virialized, but in which there is actually a continuous processing of material, since on the one hand the cloud is accreting mass from the outer infalling material, and on the other hand it is losing mass through consumption by SF and evaporation by the feedback. In this case, termination of the SF episode probably requires the termination of the gas reservoir involved in the global collapse, and is independent of the feedback. However, this need not be in contradiction with the low observed global efficiency of SF, if only a small fraction of a GMC's mass is involved in the collapse at any moment in time, with the rest being either supported (by, e.g., the magnetic field), or in the process of dispersal (Elmegreen 2007). Alternatively, the SF episode may be terminated upon the initiation of supernova events, which we have not included in the present study.

An additional consequence of the mechanisms described in this paper is that the most massive clouds appear to actually contain more mass when feedback is included than when it is not. This suggests that, first, unimpeded SF is more efficient at removing mass from the dense gas phase to deposit into stars, than the evapo-

ration of dense gas by the stellar feedback, so that, when the latter inhibits SF, the accretion onto the cloud accumulates larger amounts of dense gas than otherwise. Second, this indicates that the deposition of the feedback energy into the clouds is accurately targeted to gas that is already on the verge of forming stars. If this gas is a minor fraction of the total dense gas in a cloud (i.e. SF is a highly spatially intermittent phenomenon in molecular clouds; Vázquez-Semadeni et al. 2009), then its destruction is a highly efficient way to reduce the SFE without destroying a large fraction of the cloud.

Finally, we have also investigated the density PDF in the volumes containing the clouds in our simulations, finding that in general they retain the bimodal shape characteristic of thermally bistable flows. The PDF of the dense gas exclusively shows no turnover at low densities, indicating that low densities are most abundant. The high-density tails of the PDFs have power-law shapes, as expected for softer-than-isothermal flows, although this last result may be biased by our usage of a single cooling law appropriate for atomic gas, and extrapolating it to molecular-gas densities, rather than using a specific molecular cooling law. We expect to address this shortcoming in future works.

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